CONTROLLED EXPERIMENTS ON INSTABILITIES AND TRANSITION TO TURBULENCE ON ELLIPTIC CONES AT HYPERSONIC MACH NUMBERS

AFOSR F49620-98-1-0281

Thomas C. Corke
University of Notre Dame
Aerospace & Mechanical Engineering Department
Hessert Center for Aerospace Research
Notre Dame, IN 46556

Summary

This work involves the study of instabilities and transition to turbulence in boundary layers on cones at different angles of attacks at high supersonic and hypersonic Mach numbers. It utilizes facilities at NASA Langley Research Center which make use of "quiet" design nozzles to minimize the level of acoustic disturbances. The experiments include design Mach numbers of 3.5, and 8.0, and involve two models. The first is a 7° half-angle circular cross-section cone which has been previously used by us (Cavalieri, 1995; Corke & Cavalieri. 1997; Corke, Cavalieri & Matlis, 1997) in experiments without angle of attack, at Mach 3.5. We used this model during the past year in order to investigate the effects of angles of attack and free-stream disturbances at Mach 3.5. The second model was designed and constructed during the past year. It consists of a 10° half-angle cone with a 4:1 elliptic cross-section. The cone mounts on a sting which places it inside the worst-case estimate of the location of the quiet zone in the new Mach 8 tunnel at NASA LaRC. The model is annealed and hardened to withstand the 900°F free-stream temperature and maintain a polished finish. A 3-D traversing mechanism capable of following the tapered elliptic surface, and operating at high temperatures in the hypersonic flow is presently being built. This will carry a miniature pitot probe or hot-wire sensor. Preliminary measurements with the elliptic cone at Mach 8 are planned for October.

Mach 3.5 Experimental Setup

In the first year of the program, we utilized our existing sharp-tipped circular cone at different angles of attack, to study cross-flow conditions which would be similar to those that are expected to occur on the elliptic cone. These experiments were conducted in the Mach 3.5, 0.5m tunnel at NASA Langley Research Center, and involved angles of attack of $0° \leq \alpha \leq 4.2°$. Using the half-angle of the cone, $\phi_c = 7°$, the normalize angles of attack were $0 \leq \alpha/\phi_c \leq 0.6$. These encompass all of the dimensionless angle of attacks examined by Stetson (1982), and all but the highest angle ($\alpha/\phi_c = 0.8$) of King (1992). A summary of our experimental conditions are listed in Table 1. The coordinate system for the experiments is shown in the schematic in Figure 1.

A hot-wire was used to make time-resolved measurements in the boundary layer. In the set of measurements presented here, only a single overheat of 1.6 was used. This overheat was monitored and held fixed as the sensor was moved to different spatial positions. In some cases

Table 1: Circular Cone Experiment Conditions

$M_\infty = 3.5$, $\phi_c = 7°$			
$P_0 = 25$psi, $T_0 = 100°$F			
α (°)	α/ϕ_c	$x(in)$	θ (°)
0.0	0.0	4-12	0
0.6	.09	5-12	0, +45
1.2	0.17	7-12	0, +45
1.8	0.26	5-12	0, +45
2.3	0.33	5-12	0, +45, +135, +180,
4.2	0.60	6-12	0, +10, ±15, ±30, ±45

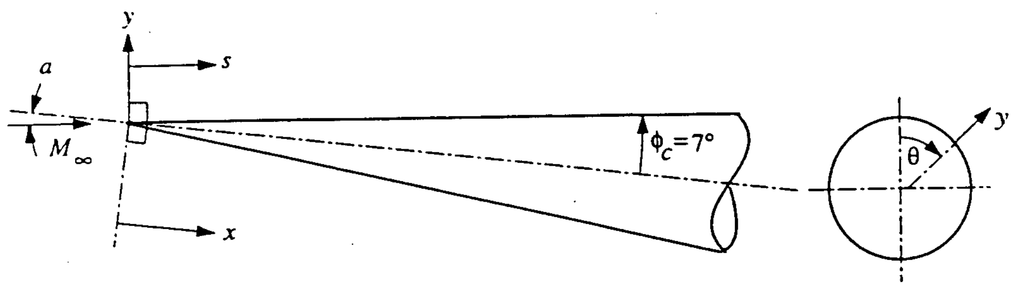

Figure 1: Scale drawing cone showing the measurement coordinate system.

(not presented here), time series at spatial locations were acquired at 10 overheats, which corresponded to values used in calibration runs with known T_0, P_0 and M_∞ conditions.

The results presented here, at a fixed overheat, are shown in terms of spectra of the anemometer voltage fluctuations. As a result of the high (fixed) overheat, we expect these are primarily representative of mass-flux fluctuations. In any event, they are sufficient to show the character of instabilities in the linear and weakly nonlinear regimes.

The measurements generally consisted of taking discrete points in the wall-normal direction at different axial and azimuthal locations. For these, the sensor was first traversed towards the wall until the wire supports made electrical contact. This method of establishing the reference height of the sensor above the wall was found to be repeatable to within 0.0005in.

Sample Results: $\alpha/\phi_c = 0.6$

The results presented here correspond to the highest angle of attack examined (Table 1). The method for increasing the angle of attack is illustrated in Figure 2. In this, shims were placed between the two parts of the vertical strut that supported the model sting in order to set the angle. Included in these drawings are the streamwise location of the start of uniform Mach number flow, and the triangular wedge region of the low acoustic (quiet) zone. The finer cross-hatched region marks the spatial extent where measurements were taken. All these are shown to-scale. The left schematic shows the configuration when the

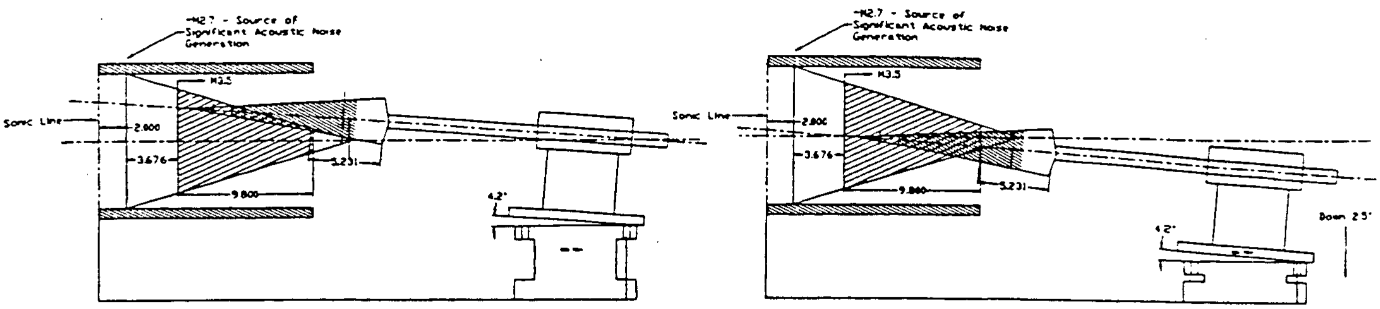

Figure 2: Scale drawing of cone position with respect to the quiet zone in two configurations at the highest angle of attack.

original lower half of the strut was used. The right schematic shows the configuration with a **modified** lower-half strut. What is evident from these two drawings is that in the left configuration, at the higher angle of attack, a substantial part of the cone is outside the quiet zone. This posed an interesting condition which we examined in detail. King (1992) had investigated the effect of completely eliminating the quiet zone (by turning off the boundary layer bleed) on the transition line. In our case, examining any differences between the two configurations in Figure 2 presented a more subtle analysis of the response of the instabilities to free-stream acoustic disturbances. Because our measurements were time-resolved, we could perform frequency analysis which was missing in King's experiment. The two studies are however, very complimentary.

Sample spectra of anemometer voltage fluctuations at different heights (y) above the wall, for different θ and x locations showed broad peaks (O40kHz) whose locations and intensities varied with y and θ.

In order to quantify some of the differences in the spectra, we analyzed the amplitude of fluctuations in 10kHz-wide bands of frequencies, starting at 20kHz. A representative sample is shown in Figure 3. There the amplitudes in these bands are plotted as a function of the y-position for different θ-positions, at $x = 9.75$in. At each θ, the lowest frequency band is at the bottom, and θ increases from left to right. The upper plots correspond to when the cone was in the left configuration shown in Figure 2. The lower plots correspond to the right configuration in Figure 2.

The wall-normal distributions in Figure 3 are consistent with the theoretical eigenfunctions for the instability modes in this flow. In addition, they clearly indicate differences in the distribution of energy in fluctuations in the boundary layer. In particular there is a dominance of lower frequencies, especially for $\theta \leq 30°$, when the cone is primarily outside the quiet zone. The difference is less at the larger θ position, although the maximum amplitudes are significantly larger in the lower disturbance condition. Similar plots at different x-locations document differences in the streamwise development which results from the different disturbance levels. Further analysis is needed, however the results point to the spatial sensitivity of the evolving instabilities to external disturbances, and the need to quantify and control these.

Elliptic Cone Design and Construction

Also during the 1st year of the grant, we completed the design and fabrication of the elliptic cross-section cone and support sting, which will be used in the Mach 8 tunnel at NASA

LaRC. Photographs of the cone and sting are shown in Figure 4. All these components are fabricated from 416 stainless steel. The cone is annealed and hardened to withstand the 900°F tunnel temperature, and to maintain a polished finish.

The length of the sting was designed to place the cone within the quiet zone in a worst-case condition of premature transition on the nozzle side-walls caused by any misalignment at the first nozzle joint location. Figure 5 shows a schematic view of the cone placement in the nozzle, and the disturbance Mach lines in this worst-case condition. Preliminary tests with the model at Mach 8 are planned for October of this year.

The final design and fabrication of the traversing mechanism is now being completed. A schematic drawing of this design on the cone is shown in Figure 6. It will be capable of moving in all three space directions over most of the cone surface.

Acknowledgment/Disclaimer

This work is sponsored by the Air Force Office of Scientific Research under Grant F49620-98-1-0281, which is monitored by Dr. Steven Walker. The facilities are provided by NASA Langley Research Center with the help of Steve Wilkinson and William Sellers. The views and conclusions contained herein are those of the author and should not be interpreted as necessarily representing the official policies or endorsements either expressed or implied, of the Air Force Office of Scientific Research or the U.S. Government.

References

1. Cavalieri, D. A. 1995. On the Experimental Design for Instability Analysis on a Cone at Mach 3.5 and 6 Using a Corona Discharge Perturbation Method. M.S. Thesis, Illinois Institute of Technology.

2. Corke, T. C. & Cavalieri, D. A. 1997. Controlled Experiments on Instabilities and Transition to Turbulence in Supersonic Boundary Layers. *AIAA Paper 97-1817.*

3. Corke, T. C., Cavalieri, D. A. & Matlis, E. 1998. Controlled Experiments on Instabilities and Transition to Turbulence in Supersonic Boundary Layers. in preparation NASA CR.

4. King, R. A. 1992. Three-dimensional Boundary Layer Transition on a Cone at Mach 3.5, *Exp. Fluids*, **13**, 305.

5. Siddiqi, M. 1996. Design of Elliptic Cone and Traverse Mechanism for Transition Studies in Mach 8 Flow. M.S. Thesis, Illinois Institute of Technology.

6. Stetson, K. 1982. Mach 6 Experiments of Transition on a Cone at Angle of Attack. *J. Spacecraft and Rockets*, **19**, 5, p.397.

7. Wilkinson, S. P., Anders, S. G., Chen, F. J. and Beckwith, I. E. 1992. Supersonic and Hypersonic Quiet Tunnel Technology at NASA Langley. *AIAA Paper No. 92-3908.*

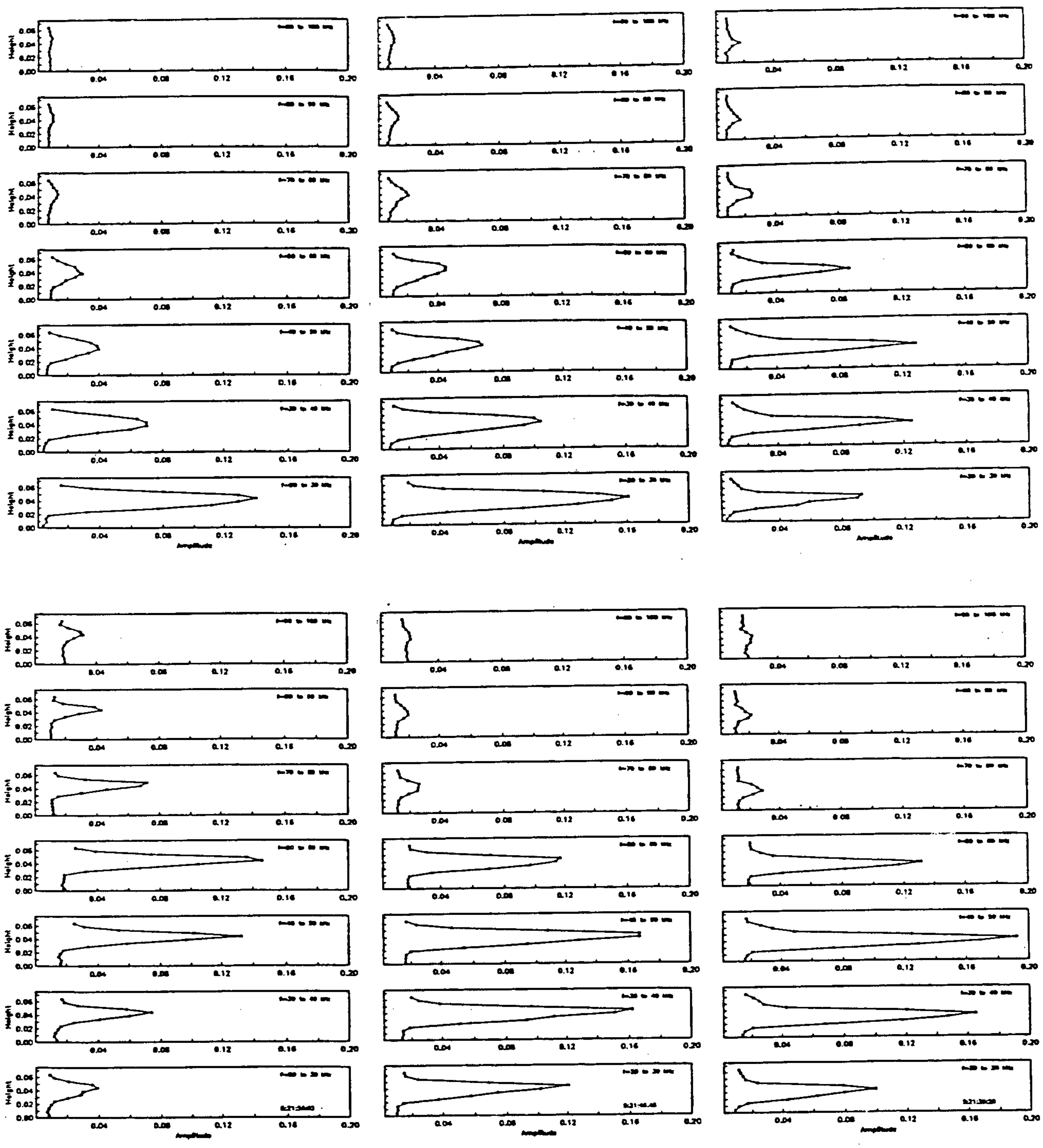

Figure 3: Wall-normal distributions of voltage fluctuation amplitudes in 10kHz bands for (from left to right) $\theta = 15, 30$ & $45°$, outside quiet zone (top) and inside quiet zone (bottom): $x = 9.75$in, $\alpha/\phi_c = 0.6$.

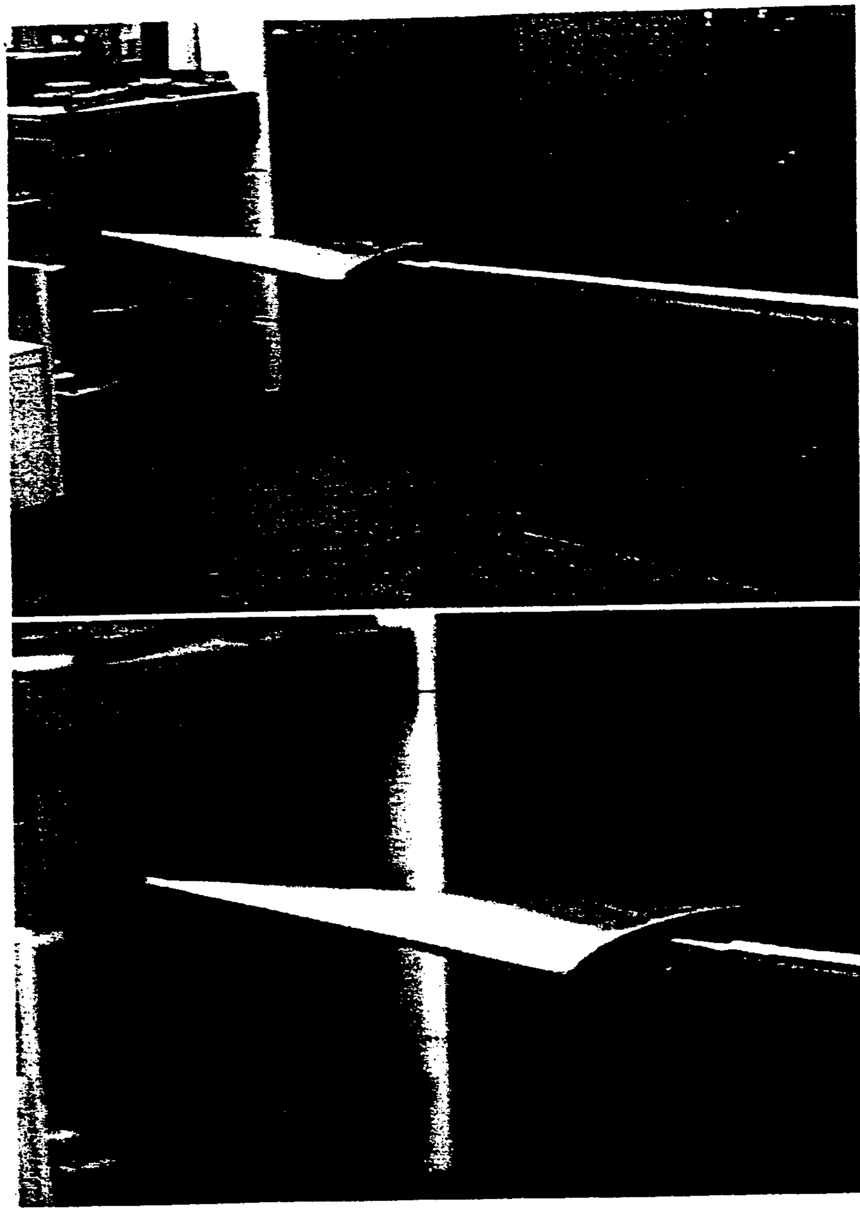

Figure 4: Photographs of elliptic cross-section cone and support sting for Mach 8 experiment.

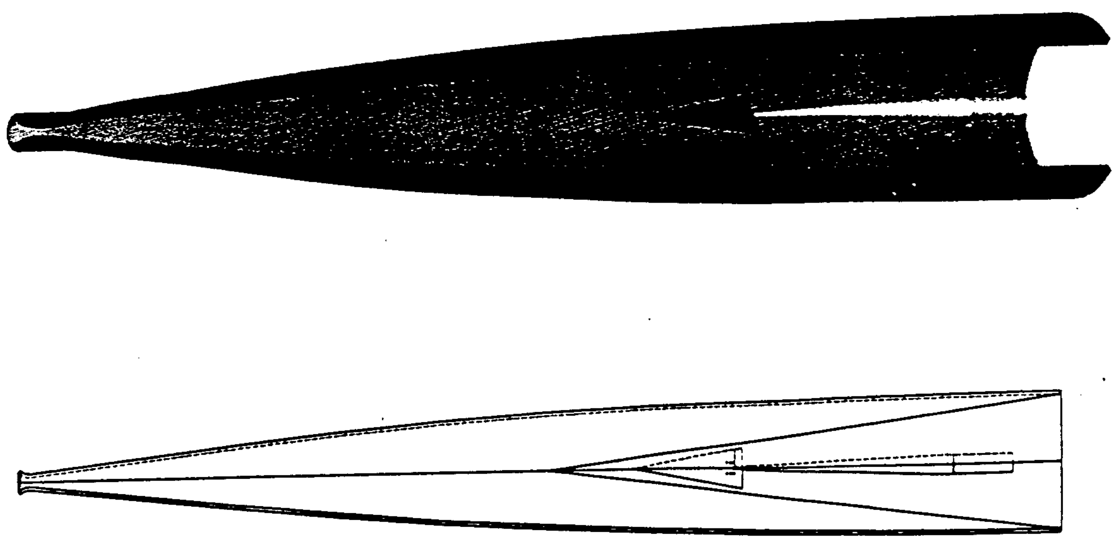

Figure 5: To-scale schematic view of elliptic cone and sting in Mach 8 quiet nozzle.

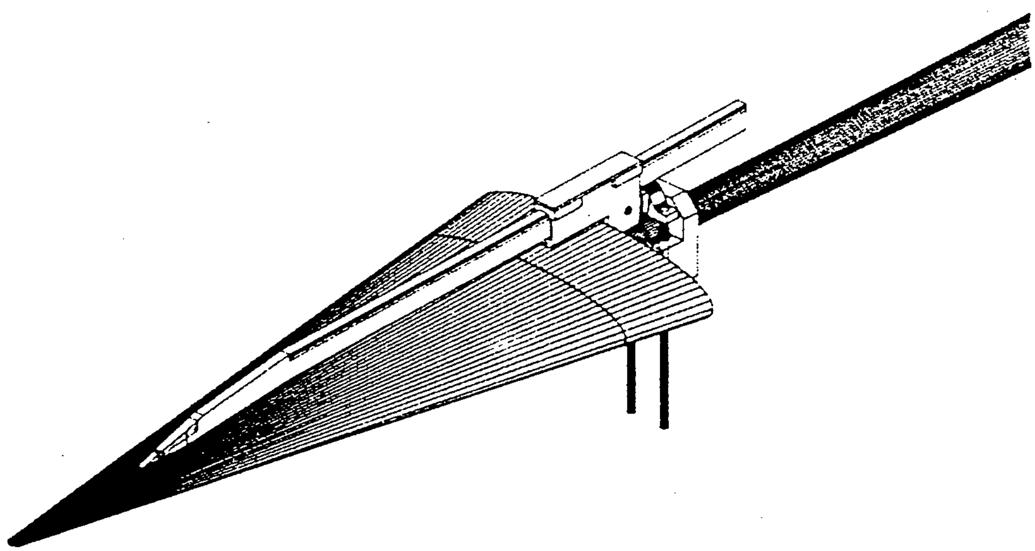

Figure 6: Schematic drawing of traversing mechanism design for elliptic cone.

REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-00-

0550

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	10/13/00	Final Report - 01 Feb 98 To 31 Oct 99

4. TITLE AND SUBTITLE
CONTROLED EXPERIMENTS ON INSTABILITIES AND TRANSITION TO TURBULENCE

5. FUNDING NUMBERS
F49620-98-1-0281

6. AUTHOR(S)
Dr. Marek Dollar

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Illinois Institute Of Technology
3300 S. Federal St.
Chicago ILL 60616-3732

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NA
801 N. Randolph St. Room 732
Arlington VA 22203-1977

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT

Unclassified Unlimited Distribution

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
This work involves the study of instabilities and transition to turbulence in boundary lay-ers on cones at different angles of attacks at high supersonic and hypersonic Mach numbers. It utilizes facilities at NASA Langley Research Center which make use of "quiet" design nozzles to minimize the level of acoustic disturbances. The experiments include design Mach numbers of 3.5, and 8.0, and involve two models. The first is a 7° half-angle circular cross-section cone which has been previously used by us (Cavalieri, 1995; Corke & Cavalieri. 1997; Corke, Cavalieri & Matlis, 1997) in experiments without angle of attack, at Mach 3.5. We used this model during the past year in order to investigate the effects of angles of attack and free-stream disturbances at Mach 3.5. The second model was designed and constructed during the past year. It consists of a 10° half-angle cone with a 4:1 elliptic cross section. The cone mounts on a sting which places it inside the worst-case estimate of the location of the quiet zone in the new Mach 8 tunnel at NASA LaRC. The model is annealed and hardened to withstand the 900°F free-stream temperature ~nd maintain a polished finish. A 3-D traversing mechanism capable or following the taperad elliptic surface, and operating at high temperatures in the hypersonic flow is presently being built. This will carry a miniature pitot probe or hot-wire sensor. Preliminary measurements with the elliptic cone at Mach 8 are planned for October.

14. SUBJECT TERMS
Instabilities and Transition to Turbulence in Boundary

15. NUMBER OF PAGES
7

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASS	UNCLASS	UNCLASS	UL